SCC flow curves from vane geometry rheometer

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Abstract The objective of the present study is to show how recording the changes in the rotation torque according to the rotation speed can lead to identifying a characteristic flow curve for the tested concrete. The concrete rheometer used for the study is composed of a vane tool. The rotation speed of the tool is imposed and the resulting torques are measured. The experimental rotation protocol used in this study corresponds to a rapid speed increase followed by a steady speed then the rotation speed slows down. The evolution of the torque measured as the rotation speed decrease (restructuring phase) is considered as being a succession of stationary states. By considering the fluid equivalent to a Bingham fluid for which the yield stress has already been identified and by using an analogy with a coaxial-cylinders rheometer, relevant relationships between the rotation speed of the vane and the rate of shearing along the tool are identified. Shear stress and shear rate calculations for each value of torque and rotation speed lead to the complete flow curve of the tested fluid. The data treatment method is adjusted to accurately evaluate the parameter linked to the flow stop in the case of a non-nil shear rate when the yield stress is reached. The comparison of the characteristic rheological parameters of SCC obtained from the rheometer and both spreading and V-Funnel tests indicate very satisfactory correlations.

Keywords: *yield stress, shear stress, shear rate, rheological parameters*

Introduction

The rheological characterisation of concretes still remains a major problem. Based on traditional geometries (coaxial cylinders, vane, and parallel-plates) different concrete rheometers have been developed [1] including two point test [2], the IBB rheometer[3], the ICAR rheometer[4-6], the BML rheometer [7,8] and the BTRHEOM apparatus [9,10] and more recently with vane geometry [11,12]. Such devices are generally characterised by a large sample volume, which complicates

the implementation of the test. The rheological characterisation of the concrete tested using these devices is generally limited to analysing the change to the rotation torque according to the rotation speed. This can be sufficient to make a comparative analysis or to study the effect of a change in concrete composition. But the links between concrete mix proportioning and rheological behaviour is not really identified.
The objective of the present study is to show how recording the changes in the rotation torque of a vane according to the rotation speed can lead to identifying a characteristic flow curve for the tested concrete. The concrete rheometer used for our study was developed by the Laboratory GCGM Rennes, France. But the method is applicable with many other devices. The data treatment method is adjusted to accurately evaluate the parameter linked to the concrete flow stop. The comparison of the characteristic rheological parameters identified on SCC from the rheometer and spreading tests and time for empting the V-Funnel is discussed.

Rheometer, test protocol and recorded data

Rheometer

The concrete rheometer used in our study was previously presented in [11] (figure 1). The device is composed of a vane tool with a 4 blades probe of 15 cm in both height h and diameter D and a cylindrical concrete container of 28 cm in diameter and 35 cm in height. The walls of this container are roughened to avoid any slippage. The vane is plunged into the concrete and level with the surface, as shown in figure 1(right). During a test, the rotation speed of the tool is imposed and the resulting torque is measured using a frictionless sensor. The torque sensor has a capacity of 100 N.m. It is a frictionless sensor that also incorporates a speed sensor to measure the real speed of the tool. The rheometer's motor is monitored by a computer. The maximum rotation speed of the tool is 120 rpm. The acquisition frequency is fixed at 10 Hz. All the experimental data are recorded in real-time and directly displayed in a spreadsheet.

Figure 1. Vane rheometer and data recorder.

Test protocol and representative records

The experimental rotation protocols used in this study are presented in figure 2. A quick and short speed increase is followed by a steady speed then the rotation speed slows down. This first step allows the static yield stress to be estimated that is characteristic of the initial state (more or less structured) of the concrete, then to rapidly de-structure it to reach a stationary state as the rotation speed slows down. This last part will be used to plot the flow curve.

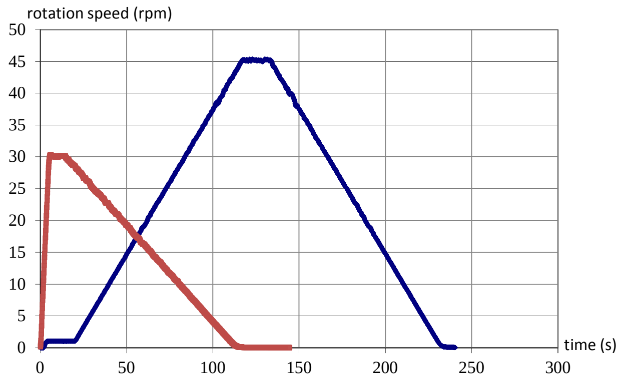

Figure 2. Examples of imposed rotation speed of the vane.

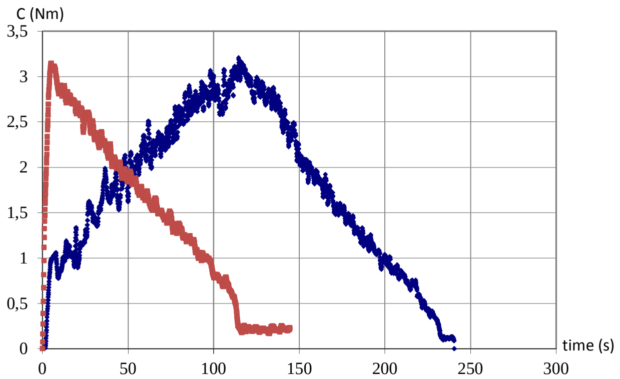

Figure 3. Examples of recorded torque evolution.

Recorded data can be seen in figures 2 and 3. With rapid increase of speed, the maximum torque is obtained in practice before reaching the constant rotation speed (figure 3). The torque reduces significantly during the constant phase (destructuring effect), then the decline is more regular. At the end of the test, we note a rapid decline of the torque as the vane stop (dynamic yield stress). Lastly, the torque may not return to zero at the end of the test (residual torque associated with elastic-plastic effects as the flow stop). Finally, it is observed that experimental data appear noisy probably due to presence of aggregates.

Data treatment methods

Dynamic yield stress and Shear stress

The evolution of the torque measured as the rotation speed decreases (restructuring phase) is considered as being a succession of stationary states. We notice that these curves are quite linear overall and have an intercept with torque axis which directly reflects the existence of a dynamic yield stress at flow stop τ_0. This value, which constitutes the first rheological parameter for the behaviour of concretes, is estimated from intercept torque C_0 tacking into account the bottom effect:

$$\tau_0 = \frac{2C_0}{\pi D^2 (h + \frac{D}{6})} \tag{2}$$

In our test configuration, the vane is plunged into the concrete and level with the surface. We therefore overcome the surface shearing effects but the bottom effect are still present. We consider that the torsion flow associated with what occurs under the vane tool contributes to the torque applied to the vane. However, as the distance between the bottom of the tank and the lower surface of the tool is great (20 cm), the contribution of the viscous component of the rheological behaviour on the torque related to this zone under torsion will be ignored. Only the contribution of the yield stress will be considered.

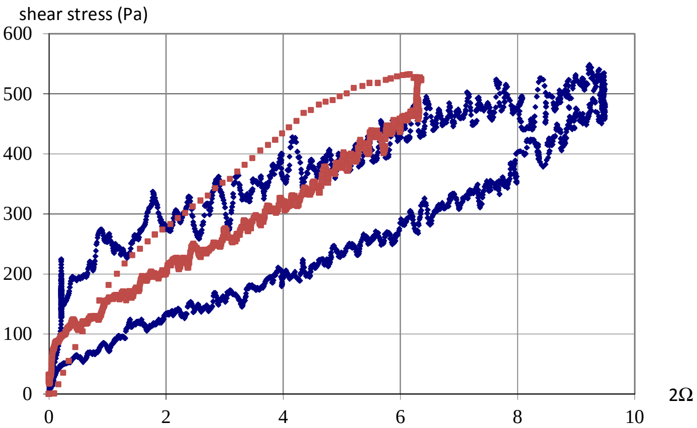

Figure 4. Examples of $\tau(2\Omega)$ curves obtained for two different SCC.

The shear stress τ applied on cylindrical shearing surface will therefore be estimated taking into account a shear stress equal to τ_0 applied to the surface of the base of the tool:

$$\tau = \frac{2(C - \frac{\pi D^3 \tau_0}{12})}{\pi D^2 h} = \frac{2C}{\pi D^2 h} - \frac{D\tau_0}{6h} \tag{3}$$

The figure 4 present the evolution of the shear stress versus 2Ω (Ω is the angular rotation speed) during a test realised on two different SCC and with the two different tests protocols (figure 2 and 3).

Shear rate calculation

A relevant relationship between the rotation speed of the vane and the shear rate induced within the gap is needed. The proposed method developed in [13], appears as a simplification of the data treatment issued from [14] and applied for flow curve identification of several materials from Couette analogy [15]. The main interest of this approach is the identification of the tested fluid flow curve without assumption on the rheological behaviour type. The initial method is based on the evaluation of the local $\tau(2\Omega)$ curve slope as an extension of the method proposed by [16,17] in the case of infinite media. This method produces more accurate flow curves than those produced assuming a homogeneous shear [18] and does not require the rheometer calibration as mentioned by [19]. Data treatment is easier than applying the wavelet-decomposition [20] but is not fully operational for noisy data [21]. So, the outer cylinder is considered equivalent to the inner wall of the rheometer container (radius R_e) while the vane represents the inner cylinder (radius R_i). In this approach, it is assumed that SCC presents a record $\tau(2\Omega)$ mainly linear (figure 4). Two configurations are studied corresponding to fully or not fully sheared gap between cylinders. Considering the fluid equivalent to a Bingham fluid for which the yield stress has already been reached and identified (equation (2)), the plastic viscosity noted μ is estimated for each value of $\tau(\Omega)$. Detail of the calculus are in [13]:

$$\Omega = \int_{Ri}^{r} \frac{d\omega}{dr} dr = \int \frac{\dot{\gamma}}{r} dr = \int \frac{\tau(r) - \tau_0}{\mu r} dr = \frac{\tau - \tau(r)}{2\mu} - \frac{\tau_0}{\mu} \ln\left(\frac{r}{R_i}\right) \tag{4}$$

In the case of a partially sheared gap, with R_p the radius for which $\tau = \tau_0$ (then $\tau < \tau_0.R_e^2/R_i^2$.), the shear rate is obtained with:

$$\dot{\gamma} = \frac{2\Omega}{1 - \frac{\tau_0}{\tau - \tau_0} \ln\left(\frac{\tau}{\tau_0}\right)} \tag{5}$$

In the case of a fully sheared gap ($\tau > \tau_0.R_e^2/R_i^2$.), the shear rate is obtained with:

$$\dot{\gamma} = 2\Omega + \frac{2\tau_0}{\mu} \ln\left(\frac{R_e}{R_i}\right) + \frac{\tau}{\mu}\left(\frac{R_i}{R_e}\right)^2 - \frac{\tau_0}{\mu} \tag{6}$$

Therefore if a is the mean slope of the curve $\tau(2\Omega)$, then :

$$\mu = a\left(1 - \left(\frac{R_i}{R_e}\right)^2\right) \tag{7}$$

In this case, the relationship between a and μ is constant.
Shear stress and shear rate calculations for each value of torque and rotation speed allow a comprehensive flow curve of the tested fluid to be plotted when τ, τ_0, a, R_i

and R_e are known. Proposed relationships appear easy to use in the case of noisy records, such as those obtained with SCC, comparing to relationships proposed in many bibliographical references. Figure 5 shows a comparison of the flow curves obtained by a shearing speed approximated by $\dot{\gamma} = 2\Omega$ [18] and for a shear rate calculated according to the equations (5) and (6). The obtained flow curve differs largely from $\tau(2\Omega)$ curve and from the fit of Reiner- Riwlin equation (straight line). Under the dotted line, the gap is partially sheared and fully sheared above. The flow curve is quite linear and highlights a Bingham rheological behaviour with presence of critical shear rate. The intercept of this curve with shear stress axis differs from the calculated yield stress value (respectively τ_0 = 40 and 70 Pa).

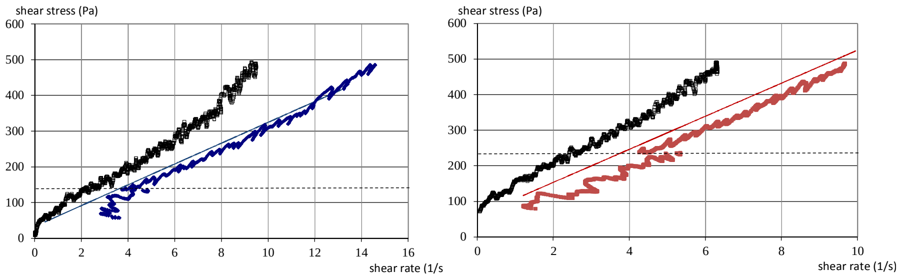

Figure 5. Examples of flow curves without correction of the initial data τ=f(2Ω) (black curves) and with correction on the shear rate (colored curve). The straight line corresponds to the fit of "Reiner – Riwlin" equation on data from figure 4.

Method adjustment

We can see in certain cases that the shear stress curve shows a non-nil shear rate when the yield stress is reached, as presented on figure 5. This trend is directly connected to the existence of a critical shear rate beyond which the flow is not stable. An alternative data treatment method is proposed to accurately evaluate the flow curve. The rheological behaviour of the fluid is also assumed as a Bingham fluid. The yield stress is obtain for a critical shear rate value $\dot{\gamma}_c$. Under this value, flow does not occur. The intercept of flow curve with shear stress axis is noted τ_{00}. The yield stress value is estimated according to equation (2) and the plastic viscosity with the equation (7). The equation (4) is then rewritten replacing τ_0 by τ_{00} and $\tau(r) \geq \tau_0$. Assuming the Newtonian approximation is right when the gap is fully sheared (ie r = R_e and $\tau(r) = \tau_0$) the following equation is obtained:

$$\Omega = \frac{\tau}{2\mu}\left(1-\left(\frac{R_i}{R_e}\right)^2\right) - \frac{\tau_{00}}{\mu}\ln\left(\frac{R_e}{R_i}\right) = \frac{(\dot{\gamma}-\dot{\gamma}_c)}{2}\left(1-\left(\frac{R_i}{R_e}\right)^2\right) \tag{8}$$

Then, the estimation of τ_{00} is given by:

$$\tau_{00}\ln\left(\frac{R_e}{R_i}\right) = \frac{\tau_0}{2}\left(1-\left(\frac{R_i}{R_e}\right)^2\right) \text{ and } \dot{\gamma}_c = \frac{\tau_0 - \tau_{00}}{\mu} \tag{8}$$

Shear stress and shear rate calculations for each value of torque and rotation speed lead to the complete flow curve (knowing τ, τ_0, τ_{00}, μ, R_i and R_e). In the case of a partially sheared gap:

$$\dot{\gamma} = \frac{2\Omega + \dot{\gamma}_c}{1 - \frac{\tau_{00}}{\tau - \tau_{00}} \ln\left(\frac{\tau}{\tau_0}\right)} \tag{9}$$

In the case of a fully sheared gap, the shear rate is obtained with:

$$\dot{\gamma} = \frac{2\Omega + \frac{2\tau_{00}}{\mu} \ln\left(\frac{R_e}{R_i}\right)}{\left(1 - \left(\frac{R_i}{R_e}\right)^2\right)} - \frac{\tau_0}{\mu} + \dot{\gamma}_c \tag{10}$$

Flow curves of SCC

The SCC tested by [13] are produced starting from a reference composition. 25 different SCC compositions deriving from this reference composition (changing content of water, of admixture, of fillers, of cement…) were tested. While composition is changed, all these concrete behaves as Bingham material. So the plastic viscosity of the SCC can estimated from the slope of the flow curves.

In parallel with the rheometer tests, the rheological properties of studied SCC were evaluated at the same time using conventional tests: slump tests (to estimate the dynamic yield stress) and V-Funnel tests (to estimate an equivalent viscosity). In practice, these tests are carried out just before the rheometer test. The slump of fresh concrete is measured using the Abrams cone according to conventional professional rules [22]. The dynamic yield stress can be estimated from the formula proposed by [23]. The flow time is evaluated using a V-Funnel [24] (figure 2) with an opening of 75 mm x 75 mm. Its height is 575 mm and its length at the top is 500 mm. Domone and Jin [25] showed that the flow time of concrete from the V-Funnel is correlated to its viscosity. Based on flow condictions and dimensions of V-Funnel, the viscosity of SCC was calculated from an analogy with the flow of Marsh cone test [26].

The comparison of the characteristic rheological parameters identified from the rheometer and spreading and V-Funnel tests indicate very satisfactory correlations (figure 6). The points in the black circle on figure 6 correspond to tests where segregation of concrete was noticed or for which sample production has been poorly controlled.

The case of a rheological study realized on a fluid concentrated suspension composed with fine coarse aggregates, admixtures and water is used to demonstrate the interest of the revised version of the data treatment method tacking into account the presence of a critical shear rate on the flow curve. The tested fluid is formulated without binder and is used as a reference fluid to compare the results of various apparatus. The flow curves obtained using three reference data treatment method and our two approaches are compared (figure 7). The first reference method consist in the use of infinite media solution [16,17]. The second correspond to the Newtonian approximation and the third is the Couette analogy. Our proposed methods highlight the presence of a critical shear rate expected for the tested fluid. The discrepancy between the obtained flow curves are significant.

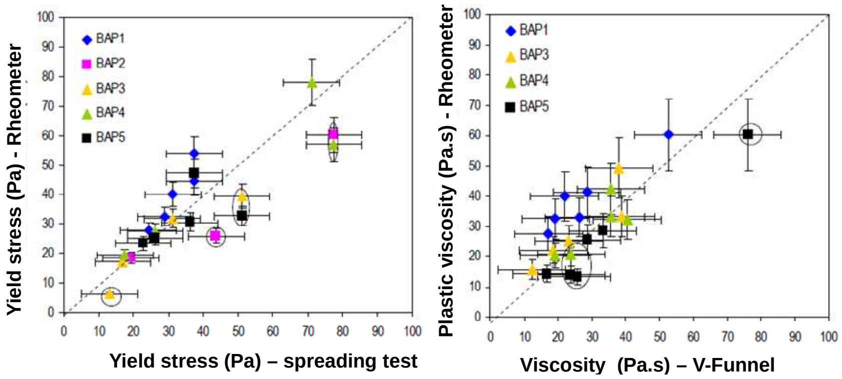

Figure 6. Correlation between the yield stress estimated by slump test and the dynamic yield stress measured using the concrete rheometer and correlation between the apparent viscosity evaluated using the V-Funnel and the plastic viscosity measured using the concrete rheometer [13].

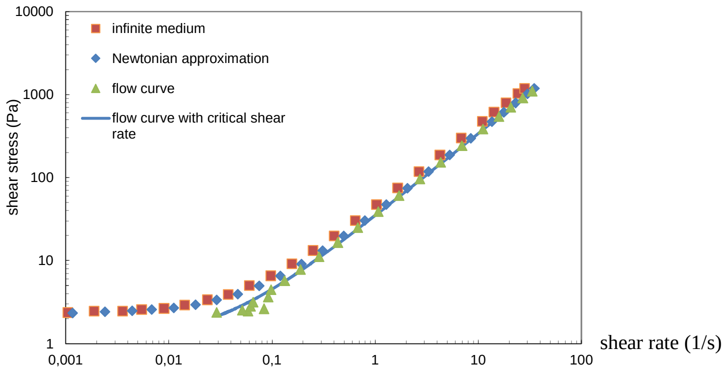

Figure 7. Comparison of flow curves obtained starting from torque measurement on a fluid concentrated suspension and using various data treatment method.

The proposed data treatment method lead to a flow curve very closed to the points obtained with the equation (5) and (6) even if this method do not take into account the presence of critical shear rate. The same type of results obtained with data of a

SCC (black dot on figure 4) are presented on figure 8. The estimated critical shear rate value is 0.64 1/s and τ_{oo} = 23 Pa as τ_o = 40 Pa.

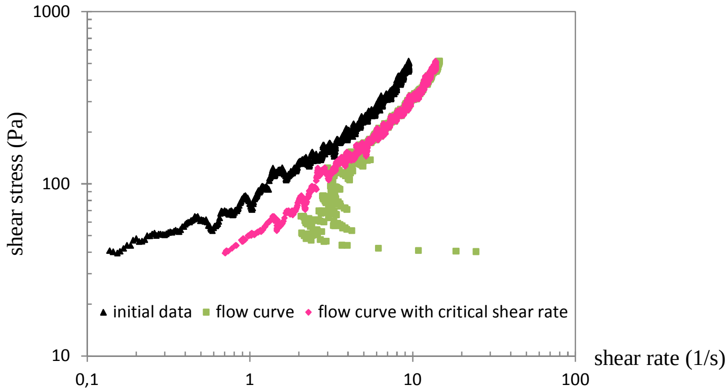

Figure 8. Comparison of flow curves obtained using various data treatment method.

Conclusions

The record analysis method proposed for identifying a characteristic flow curve for the tested fluid in a vane tool rheometer configuration has proved to be highly appropriate. In the case of self-compacting concretes, adjustment of a Bingham-type rheological behaviour on records obtained during shearing under restructuring stage has proved to be acceptable. The comparison of the characteristic rheological parameters identified from the rheometer and spreading tests – slump and time for empting the V-Funnel – indicate very satisfactory correlations, which allow studies aiming to compare concrete rheometers to be considered from a new point of view. The used data treatment method can highlight, for some concretes, the existence of critical shear rate which constitutes an interesting study perspective.

References

[1] Ferraris C.F. and Brower L.E. editors (2001), *Comparison of concrete rheometers: International tests at LCPC, October, 2000*, NISTI Report 6819.
[2] Domone P.L.J., Xu Y., Banfill P.F.G. (1999), *Magazine of Concrete Research* 51 181-190.
[3] Beaupré, D. *Rheology of High Performance Shotcrete* (1994) Ph D. Thesis Univ. Of British Columbia (Canada).
[4] Koehler, E. P. (2004) *Development of a Portable Rheometer for Portland Cement Concrete*, MS Thesis, The University of Texas at Austin (TX).
[5] Koehler, E. P., Fowler, D. W., Ferraris, C. F., Amziane, S. (2005) *A New Portable Rheometer for Fresh Self-Consolidatinng Concrete*, Proc. of session ACI 2005 (New York).

[6] Koehler, E. P., Fowler D. W. (2004) *Development of a portable rheometer for fresh Portland cement concrete*, Research report ICAR – 105-3F, Univ. of Texas.
[7] Wallevik, O.H. (1990) *The rheology of fresh concrete and its application on concrete with and without silica fume*, Dr. ing. Thesis, NTH Trondheim (Norway).
[8] Wallevik, O.H., Gjorv, O.E. (1990) *in Proceedings of the Rilem Colloquium*, Chapman & Hall, Hanover, October, 213-214.
[9] De Larrard, F., Szitkar, J.C., Hu, C., Joly, M. (1993) in *RILEM Workshop Special Concretes* Workability and Mixing, 201-208.
[10] De Larrard, F., Sedran, T., Hu, C., Szitkar, J.C., Joly, M., Derkx, F. (1996) in *Rilem International Conference on Production Methods and Workability of Concrete, RILEM Proceedings 32*, Glasgow Scotland, June 3-5, 377-388.
[11] Estellé P. and Lanos C. (2012) *Applied Rheology*, 22 12881.
[12] Soualhi H., Kadri E.H., Ngo T.T., Bouvet A., Cussigh F., Kenai S.(2014), *Appl. Rheol.* 24:2, 22594.
[13] Mokkedem S., Lanos C., Casacliu B. (2013) *Comparison of SCC rheological behavior using laboratory and in situ rheological testing*. In SCC Paris 2013, Paris, France, 2-4 septembre.
[14] Estellé P., Lanos C. (2008) *Chemical Engineering Science*, 63:24, pp. 5887-5890.
[15] Estellé P., Lanos C., Perrot A., Amziane S. (2008) *Applied Rheology*, 18:3, 34037.
[16] Nguyen Q. D. and Boger D. V. (1985) *Journal of Rheology*, 29, pp.335-347.
[17] Nguyen Q.D., Boger D.V., *Rheol. Acta* 26 (1987) 508-515.
[18] Steffe, J.F. (1996) *Rheological methods in food engineering process*, Second Edition, Freeman Press, East Lansing, (USA).
[19] Aït-Kadi A., Marchal P., Choplin L., Chrissemant A.S. and Bousmina M. (2002) *Canadian Journal of Chemical Engineering*, Volume 80, Issue 6, 1166–1174.
[20] Ancey C. (2005) *Journal of Rheology* 49(2) 441-460.
[21] Estellé P, Perrot A, Mélinge Y, Lanos C, Amziane S (2007) in *5th Int. RILEM Symposium on Self- Compacting Concrete*, Gent 3-5 septembre, vol 1, pp 291-296.
[22] AFNOR (1999), Tests for fresh concrete – Part 2: slump and spreading test, NF EN 12350-2. Technical report.
[23] Roussel N., Coussot P. (2005) *Journal of Rheology*, 49, 705-718.
[24] [8] AFNOR (2010), Test for fresh concrete – Part 9: self-compacting concrete – V-funnel flow test, NF EN 12350-9. Technical report.
[25] Domone P. L. and Jin J. (1999). In *Proceedings of the RILEM Symposium on Self-Compacting Concrete*, pp. 109-120, Stockholm.
[26] Frunz L., Lootens D., Flatt R.J., Wombacher F., and Velten U. (2010). In *RILEM Proceedings, Design, Production and Placement of Self-Consolidating Concrete*, Montreal 2010, Volume 1, Part 2, pp.53-63.